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MEASURING SOIL MOISTURE

by

F. Cope and E. S. Trickett

(C.S.I.R.O., Irrigation Research Laboratory, Griffith, N.S.W., Australia)

Introduction

Methods available to determine the moisture status of the soil are unsatisfactory in various ways, so that few find wide acceptance. There is a particular need for quick and accurate methods for measuring soil moisture *in situ* without undue damage to the site, and this point is emphasised in this review. The more worthwhile methods which have been proposed are listed with mention of their advantages and limitations, and some new methods born out of recent advances in technology are discussed. For further study attention is directed to the bibliography by Shaw & Arble (1959), and the reviews of Marshall (1959), Taylor et al (1961), Johnson (1962), and Pande & Pande (1962a, b, c, d). Methods are listed here under the headings: thermo-gravimetric, lysimetric, penetration, chemical and nuclear, which estimate the amount of soil moisture; and tensiometric, pressure, vapour pressure, thermal, and electrical which in general measure the energy of the moisture.

Soil sampling. Most methods involve making a hole either for the removal of a sample or the insertion of an instrument. Tools for this purpose range from trowels to power augers. Soil augers and sampling procedures are detailed by Lull & Reinhart (1955) and Johnson (1962). The type of sampler in most common use is described by Veihmeyer (1929), and a useful variant of this by Stace & Palm (1962). A good sampler will allow uncontaminated samples to be taken as quickly as possible from the required depth with minimal damage to the site. Holes made should be filled, but damage to plant roots and the introduction of variable drainage and infiltration characteristics may be unavoidable. Since much replication is needed to characterize a typical experimental site adequately (Fitzgerald & Richard, 1963) disturbance is considerable. Continuity of measurement from the same precise spot is impossible. These limitations do not apply to *in situ* methods since instruments may be installed, in few holes, before measurements commence. For some projects samples may be taken more quickly with power tools (Wells, 1959), perhaps at the expense of more damage to the site.

Measuring the Amount of Soil Moisture

Thermo-gravimetric methods. The thermo-gravimetric method is a basic one in general use, and used for the calibration of other methods. Samples are taken and placed in tared containers. They should be weighed as soon as possible, but careful sealing and cool storage will reduce errors to a minimum (Sabitov, 1961). The moisture content is determined by drying samples at 105°C to constant weight in a thermostatically-controlled oven. The weight of water lost is expressed as a percentage of the dry-soil weight. Drying and weighing procedures are slow, but may be speeded by using infra-red (Popov, 1960) or vacuum-drying and an automatic balance. Apart from such expensive modifications the method has the advantage of requiring simple equipment which is commonly available. It is accurate on the sample used, and, with adequate replication, for the site. Samples may be useful, or essential, for some other purpose such as chemical analysis. The chief disadvantages are those implicit in taking and handling samples, they are particularly tedious where correction must be made for the variable content of stones and gravel in samples.

The other methods under this heading generally use even simpler apparatus, or purport to speed operations. Wilde & Spyridakis (1962) eliminate oven-drying by shaking a weighed sample in a flask to remove air, and then weighing the flask in water. The moisture content is calculated assuming a mean value for the specific gravity of soil, thus permitting simultaneous determination of bulk density. Bouyoucos (1937) evaporated the moisture from soil samples by adding alcohol and igniting, and Thijsen et al (1954) removed moisture rapidly by heating a mixture of soil and non-volatile oil to 130°C. Begemann (1936) eliminates both drying and reweighing by mixing the sample with water-free xylol and distilling so that the denser water is collected beneath xylol in a graduated tube. A similar principle is used by Teterin (1956) in his ingenious 'universal moisture meter' which consists of a heater to evaporate moisture from the sample, a condenser, and a float chamber to collect moisture. The weight of the float chamber moves a mirror which deflects a light beam onto a scale. Attempts have also been made (Davis & Slater, 1942) to determine moisture repeatedly at the same precise location in the soil by weighing absorbent blocks used in a fixed probe, but the method is rather unreliable and gives only approximate values.

Lysimeter methods. Weighing lysimeters represent a special gravimetric technique by which continuous measurements of moisture content may be made on the same mass of soil without destructive sampling or sample-handling problems. They consist of a container filled with soil, which may be a monolith or a reconstructed profile, set flush with the ground surface. Earlier models (Harrold & Dreibelbis, 1945) were weighed with pulleys and balances, later models are supported on a subterranean weighbridge, and in some the changes in weight are recorded by load cells, a system which lends itself to automatic continuous recording (Van Bavel & Myers, 1962). Load cells for which repetition accuracies of 0.05% are claimed are now available (Anon, 1961). Lysimeters are accurate for the soil volume contained, provided that correction is made for weight changes in the crop grown on them. The cost of most types prevents sufficient replication to characterize larger areas, but adequate replication is possible with small, inexpensive types of weighing lysimeter, e.g., that of Glover & Forsgate (1962). These are a development of larger hydraulic lysimeters such as that of King et al (1956). In these smaller units changes in weight of the soil container produce changes in pressure in a water-filled flexible bag on which the container rests. Winter (1963) describes a more sensitive lysimeter of this type in which most of the soil weight is supported by buoyancy in water. He claims a sensitivity of 0.01 in. of water, and this is confirmed by the writers. Although these lysimeters are sensitive to changes in ambient temperature, errors can be minimized by burying them flush with the ground surface and corrections made from a blank installation in which the surface is sealed. In a hot climate a close-fitting floating lid and a layer of cetyl alcohol can reduce excessive evaporation from the outer container.

Penetration methods. Simple penetrometers give a rough indication of soil moisture from the depth of penetration of a pointed probe; more elaborate types measure the force required with a dynamometer mounted in the probe handle. Allyn (1942) claims an accuracy of 0.5% moisture for a probe having a diamond-shaped blade, the torque required to rotate the blade being measured. A variation of the penetration method is that of Koliasev & Kozlov (1954) in which moisture content and compaction are measured simultaneously on a sample of soil under fixed pressure. Penetrometers are simple, cheap, and rapid in use, although use is confined to moderate depths and to relatively stone-free soils. Calibration is needed for each soil and accuracy may be low, but they have their uses, e.g., in irrigation experiments.

Chemical methods. All chemical methods are used on samples and suffer the disadvantages attendant upon these. Most are intended as rapid methods and one, the carbide method, has been used extensively for civil-engineering purposes so that commercial equipment is available. The soil sample is intimately mixed with calcium carbide and the pressure of acetylene generated within a closed system is a measure of the moisture content (Danne, 1912). Errors may arise from the presence of calcium oxide and other impurities in the carbide used, but an accuracy better than ±0.5% moisture is claimed (Heissner, 1961). The Karl Fischer method is used in industry for the determination of moisture in chemicals and accepted as a standard by the American Society for Testing Materials (Fraade, 1963). Solid samples must be dissolved or, if insoluble, leached with a suitable solvent which is then titrated against a solution of iodine sulphur dioxide and pyridine in methanol. This reagent is costly and requires frequent standardization. Visual determination of the end point may lead to error, but this can be avoided, and titrations made rapidly, by using relatively expensive automatic titration equipment.

Bouyoucos (1928) estimated soil moisture by measuring the change in specific gravity of alcohol used to displace it. Similarly Hancock & Burdick (1957) used an alcohol-acetone salt system to displace water in wet soils, then measured the change in conductivity of the system in a conductivity cell, making a correction for the temperature coefficient of conductance of the system. Various other rapid chemical methods have been proposed (Shaw & Arble, 1959) but these are of doubtful value.

Nuclear methods. The most successful nuclear method to date depends on the scattering of neutrons. The bibliographies of Sweeny (1962) and Shaw & Arble (1959) list most of the papers which describe the method, which received its impetus from use in civil engineering. Holmes (1956) and Van Bavel (1958) describe its application in agriculture. A probe unit contains a fast-neutron source, usually 5 mc of radium 226 or actinium 227 mixed with beryllium, with a long half-life; and a slow-neutron detector, e.g., a tube filled with lithium-enriched boron trifluoride gas. Most of the hydrogen in all but highly organic soils is in the soil moisture, and this hydrogen slows down fast neutrons to a far greater extent than any other element found in significant amounts in most soils. When the probe is placed in soil some of the reflected slow neutrons resulting from collision of fast neutrons with hydrogen nuclei will traverse the volume of the detector tube and be captured. The detector has an operating potential around 1500 volts. Neutron capture results in a transient breakdown of the tube and the production of a short period pulse of current. The number of resultant pulses is proportional to the hydrogen and hence to the moisture content of an ellipsoid of soil around the cylindrical probe. A pre-amplifier in the probe amplifies the pulses so that they may be transmitted along a cable to a portable scaler which also embodies amplifier, discriminator and timer units. Probes for surface use have a typical 'flat-iron' shape. They contain a cast-iron reflector to reduce loss of upward-emitted neutrons, and detector tubes which may encircle the source. A number of commercial neutron moisture meters conform to this broad pattern and some also offer a soil-density probe with a gamma source and a Geiger detector for use with the same scaler unit.

These points should be looked for in a neutron moisture meter intended for field use. The probe should be robust, waterproof, and of small dimensions so that small-diameter access holes may be used without risk of jamming. Rigidity is essential to avoid signals due to microphony, which are not random errors but add to the count. Probe casings must compromise between strength, corrosion resistance and low neutron absorption; stainless steel is suitable since it can be used in thin sections, also some aluminium alloys. Errors of the order of ±100 in 10,000 counts arise from the eccentric placement of the source with regard to the wall of the access hole. Annular or central placement of the source should reduce this.

The scaler unit should be in a strong, light, corrosion-resistant case, e.g., resin-bonded fibre glass. The power source may conveniently be in the same case provided that components are completely protected from acid damage. Dry batteries or alkaline secondary cells are to be preferred to lead-acid types. The amplifier should accept pulses with a rise time of about one micro-second and be able to discriminate between pulses a few micro-seconds apart. A gate circuit is used to stop the count when the required time has elapsed, or, if on a pre-set count, to stop the timing system. Most scalers have 5 counting decades accumulating up to 99,999 counts but some instruments use a rate meter as a cheaper alternative.

The rate meter, with its asymptotic approach to a reading, may be simpler, but the summing counter which provides a definite intersect between a linear function and a chosen ordinate is preferable. Some economies are possible with digital counters, at least one commercial scaler uses electromechanical registers to store the higher digits. It is not even essential to display the digits so that an electronic integrator system might be used to accumulate 10,000 counts, for example, and then switch off the timer. A solenoid-operated stop watch, if used, must be reliable and should not make excessive demands on the power supply.

The neutron meter is used to determine the moisture content of a volume of soil *in situ*. Probes for measuring in the top 20 cm work effectively only on a flat surface, a condition hard to satisfy in agronomic work. On grassed sites turves may be lifted and replaced. The depth probe is used in holes bored to the required depth and lined with close-fitting tubes of steel, plastic or other suitable material of low neutron capture, to give permanence and to safeguard the probe. The probe should be a close, free fit in the tube to ensure reproducible geometry. Metal tubes are strong and may be driven into the soil to give very close contact, the bottom being sealed after emptying by augering or jetting. Tubes made from heavy-gauge polythene are sealed before being inserted in very tight-fitting auger holes. Problems of heat conduction, with expansion and contraction causing soil to crack away, and of internal moisture condensation occur with metal tubes. These are largely avoided by using plastic. Water movement down the outside of the tube, especially with irrigation, can be stopped by a small collar fitted about 15 cm down. Access tubes are cheap and can be replicated. An internal expanding mandrel will grip the tube for removal by jacking.

Advantages of the method are the accuracy and speed of reading, e.g., duplicate readings may be made at 30-cm intervals to a depth of 180 cm in 15 minutes, and the ability to take multiple readings in space and time without disturbing the site or crop. To achieve this attention must be given to the mounting and manner of use. A lightweight stable trolley with large-diameter wheels is an excellent mounting for field experiments. Site damage can be avoided by setting up off-site; one person then carries the probe to the access hole and positions it with minimum trampling while a second person takes the readings. Alternatively a pulley system may be set up to move the probe, except on windy days.

Disadvantages include the high capital cost, high maintenance costs on some inferior equipment, and the need for precautions in using radio-active materials. The source should be of the lowest intensity compatible with efficiency (Van Bavel, 1962). Some probes are supplied with heavy shields quite unsuited to field use in hot weather. A good practice is to store the probe in a tube set in the ground, or in the 40-gallon drum of water used for normalising. In use it is handled as little as possible and carried well away from the body. By taking such precautions one of the writers (F. C.) received only 212 mRem, as recorded on a film badge, over a 12-month period during which a probe with 5 mC Ra-Be source was used for about 240 hours. Inaccuracies can arise in some soils from the presence of Li, B, Cd, or other nuclei of high neutron capture, also from the presence of hydrogen in organic matter. Measurements are made in a rather ill-defined ellipsoid of soil. With a 5-mC source the vertical radius varies from 17 cm in water to 30 cm in dry soil (Holmes, 1956). This limits the degree of discrimination and leads to inaccuracies in the presence of abrupt moisture changes (Lawless et al, 1963), and also when closer than 20 cm to the surface where neutrons can leak into the air unless the special reflecting probe is used.

Another method based on nuclear physics employs the attenuation of a broad, near-parallel beam of gamma radiation to characterize moisture status. The absorption of gamma quanta is essentially a density-dependent phenomenon, and the method is not specific for water but relies on the change in effective density caused by changing moisture content. Danilin (1955) and Mukhin & Chistotinov (1961) applied the method in the field using a Co^{60} source of 20 mC and a detector in adjacent holes. Lead shields were used to collimate the beam at source and detector. The possibility of defining the layer of soil involved makes the method attractive.

Gurr (1962) and Ferguson & Gardner (1962) used the method satisfactorily in the laboratory to make continuous measurements of the water content of layers of soil in fixed columns. The nature of the source increases the potential hazard to the operator using this method.

Nuclear magnetic-resonance spectroscopy is a recent technique based on the absorption of radio-frequency energy by the nuclei of atoms placed in a constant magnetic field. Andreyev & Martens (1960) have applied this method to samples of soil, and claim accuracies of about 1% over a range of 2-50% moisture content. It is not clear whether this technique could be developed for use in the field, but Andreyev and Martens give a useful list of references for anyone interested in exploring the possibilities.

Measuring the Energy of Soil Moisture

Tensiometric methods. A tensiometer consists of a water-filled porous cup buried in the soil and connected to a manometer or vacuum gauge. Water in the cup reaches pressure equilibrium with the soil and matric suction is recorded. The cup is permeable to solutes, and solute potential is not detected. Early designs are described by Richards (1949). Most, including commercial ones, are made by glueing a porous ceramic cup to a length of rigid plastic (e.g., acetate-butyrate) tubing of about ¾-inch diameter, fitting a stopper to the other end and inserting a take-off for the gauge. Some have a double-walled tube which is said to reduce fluctuations due to temperature changes. The manometer may be attached directly, or at the end of a length of smaller-bore tubing. With this off-set arrangement the tensiometer can be buried with the stopper flush with the soil surface, thus reducing heat conduction and risk of breakage by cultivations or animals (Cope, 1962). Copper, neoprene, or rigid nylon tubing may be used to make this connexion, but an all-plastic construction is preferable, giving lower heat conduction and freedom from the corrosion which is a problem in saline soils.

Gauges and glass manometer tubes must be insulated against frost and heat, manometers can also be made from new rigid translucent nylon tubes. Weatherproof Bourdon vacuum gauges, nominally accurate to ±1% of the full range, are adequate for irrigation control, but mercury manometers accurate to 0.2% are better. For laboratory use there are more elaborate and sensitive instruments such as the null-point tensiometer of Miller (1951) and the self-adjusting instrument of Leonard & Low (1962) which uses a siphon bellows in a porous cylinder of lucite and will measure dynamic as well as static tensions. Klute & Peters (1962) describe a tensiometer with a fritted-glass cup in which the water pressure is measured by a pressure transducer of the strain-gauge diaphragm type, having a sensitivity of at least 3×10^3 millibars per cc. Auto-recording for tensiometers seems to be expensive or unreliable. One of the writers (E.S.T.) has fitted a read-out to a Bourdon gauge, but this has not been fully developed for use in the field where the best solution at present is to group gauges or manometers from several instruments in one panel and record by periodic photography.

Tensiometers are cheap and easy to construct, calibrate, and install, allowing adequate replication. Matric suction, which is a most useful measure in field experiments, is recorded directly *in situ*, and no arithmetic is required. The translation of matric suction to soil-moisture content involves individual calibration for each soil and is not a recommended procedure.

The chief disadvantage of the tensiometer is that it measures over a limited part of the suction range over which plants may survive. It is effective only from 0 to 0.85 atmosphere whereas plant wilting point is around 15 atmosphere. When soil suction exceeds about 0.8 atmosphere for more than a day, so much water is extracted from the cup that air enters and the system breaks down. The tensiometer must then be flushed out to remove air bubbles and refilled with boiled distilled water. Nevertheless tensiometers have considerable value, for in sandy soils the range 0-0.85 atmosphere may cover over 90% (Kelley et al, 1946), and even in fine-textured soils 50% (Richards, 1949) of the available moisture in the soil. Fine-textured soils will clog the porous cup, but this can be delayed by setting it in sand. Diurnal variations in temperature affect the readings of tensiometers, especially those with uninsulated parts exposed. The remedies lie in plastic construction, installing completely below ground, and reading each instrument at the same time each day.

Pressure methods. The pressure-membrane apparatus was developed by L. A. Richards (1941, 1947) to measure the uptake and release of moisture from samples of soil over a wide range of suction values. Far higher suctions can be measured than with the tensiometer, the working range being generally up to 15 atmospheres, since water content at this pressure is roughly that at permanent wilting point in many soils. The apparatus consists of a metal pressure chamber, the floor of which is a membrane of cellulose or other suitable material supported so as to withstand high pressures from the inside. Alternatively 15-bar ceramic plates are now available which allow more rapid equilibration than will a membrane. This membrane or plate will pass water and also dissolved salts (Reitemeyer & Richards ,1944), but will hold back compressed air or nitrogen when wet. Some leakage of gas does occur (Collis-George, 1952) but this does not affect routine use of the method (Quirk, 1954).

A wetted sample of soil is placed on the membrane, and gas is introduced into the chamber at the required pressure. Water then moves out of the soil through the membrane until the forces holding water in the soil just balance the gas pressure which is tending to force water out. If the pressure inside the chamber is returned to atmospheric, a suction of the same order as the original pressure would have to be applied to the water below the membrane to prevent it re-entering the soil. Thus the pressure in the chamber is equal to the suction of the soil at the equilibrium water content, except for errors, the order of which is not yet clear, due to compression and subsequent expansion of air trapped and dissolved in the sample (Peck, 1960; Chahal & Yong, 1964).

Improvements to the pressure apparatus mostly concern the control unit which must hold pressures in the 0-20,000-cm range for long periods; high precision is claimed for float-valve regulators (Hanks et al, 1953). The porous-plate apparatus of S. J. Richards (1938) operates on the same principle as the pressure membrane, commercial apparatus for this method is cheaper but the range is generally restricted to 0-1 atmosphere.

Vapour-pressure methods. In these the equilibrium humidity of an enclosed volume of air around a soil sample is used as a measure of the activity (matric + osmotic suction) of water in the soil. Orchiston (1953) describes the simple vapour adsorption/desorption technique using H_2SO_4 solutions with soil in an evacuated desiccator. Solutions of sodium chloride are preferable, although saturated solutions of various salts have advantages where the sample is large. The best published source of osmotic molal coefficients is Robinson & Stokes (1959). The method has a potential range from 1-50 atmospheres water tension. Spanner (1951) first used Peltier cooling to measure the wet-bulb depression in a small chamber containing leaf material. Monteith & Owen (1958), Richards & Ogata (1958), and Korven & Taylor (1959) have since used psychrometer methods successfully for soils. Barrs (1964) has improved earlier techniques, particularly as regards the speed of equilibration and recording. Field application appears unlikely, for all measurements must be made under precisely controlled temperature using a double-jacketed water-bath. However, the constantly improving speed and precision of the method, plus the facility with which a large number of points on the pF curve may be determined simultaneously, may make it an acceptable alternative to pressure methods.

Thermal methods. Attempts have been made to exploit the thermal conductivity of the soil directly (De Vries, 1953; Van Duin & De Vries, 1954) and that of absorbent thermal blocks in close contact with the soil (Haise & Kelley, 1946) to determine soil moisture *in situ.* Thermal conductivity is independent of salt content and this should give the method an advantage over the resistance block particularly for saline soils. Direct measurements depend upon very close contact between soil and probe—which is hard to achieve. However De Vries (1953), whose method is based on the logarithmic rise in temperature with time of an 'infinite' line source in a homogeneous medium, reports consistent results in sandy soil. In practice the source is an electrically heated wire in a needle-shaped probe 13 cm long. A thermo-junction near the centre of the wire measures temperature. A rather different technique has been tried for measurements in the laboratory (Van Wijk, 1963; Talsma, 1964) in which soil samples are heated by a 300-watt lamp mounted above. Measurements are made with a flux plate on top of the soil and thermocouples accurately located at various shallow depths; unsolved problems here are in construction of a satisfactory flux plate and the maintenance of precise system geometry. A suitable material is still needed to make the thermal-block method workable.

Shaw & Baver (1939) used a Wheatstone bridge, one arm made of enamelled copper wire wound on glass tubing being set in the soil, to follow moisture changes *in situ*; the other three bridge resistances are made of manganin. Since the input to the copper element is constant the resistance depends upon the thermal conductivity of the soil. In the method of Momin (1945) and Kubo (1953) a mercury thermometer having half the bulb wound with electrically heated wire is set in the soil. The time required to attain a constant temperature rise is said to be proportional to the soil moisture.

Electrical methods. Direct measurement of the electrical resistance of the soil by the four-electrode method is used in geophysical and hydrological surveys (Edlefson & Anderson, 1941; Taylor, 1952). Childs (1943) criticises the method since there is a large and variable capacitance component, and it is not accurate enough for field experimental plots. However, the resistance of absorbant blocks at moisture equilibrium with the soil is a function of the moisture content of the block, and can be used as a measure of soil suction. Interpretation in terms of soil-moisture percentage may also be attempted by suitable calibration. Bouyoucos & Mick (1939) used standardized blocks of plaster of paris in which are set electrodes connected by insulated wires to an A.C. Wheatstone bridge. Such blocks will measure suctions within the pF range 2.6-4.2, but improvements such as the use of nylon and of fibre-glass in blocks (Bouyoucos, 1949; Colman & Hendrix, 1949), and the use of concentric and spot-welded stainless-steel mesh electrodes (Croney et al, 1951; Postlethwaite & Trickett, 1956) have improved durability and sensitivity of blocks and extended the wet range to pF 2.

Resistance blocks must be made within close tolerances, even so individual calibration is necessary for research purposes. Haise & Kelley (loc. cit.) used a pressure-membrane apparatus for this, and Aitchison & Butler (1951) obtained best results with this when blocks were embedded in soil. Full calibration is tedious, and is sometimes remitted to one point for a homogeneous batch once the full curve is established. Calibration is usually on the drying curve since blocks display marked hysteresis (Bourget et al, 1958), and the resultant curves are not necessarily stable with time. Changes due to dissolution of the calcium sulphate cannot be checked once the block is installed, however, this does give some degree of buffering against the effect of soluble salts—a major disadvantage of the method. Many blocks are temperature-sensitive, and corrections are made either manually or from built-in thermocouples.

The resistance-block method has a number of advantages for *in situ* measurements. Blocks are cheap, and numbers can be installed in the field and read at intervals without disturbance to the site. The leads may be brought to a central point, and the method lends itself to automatic recording, e.g., on a potentiometric or bridge recorder (Bouyoucos, 1962). Blocks and measuring bridges for field use are commercially available. However the method is still lacking in reliability and precision, and will require considerable refinement, in process control for block making and in calibration techniques, before it receives wide acceptance.

The electrical properties of soil at radio frequencies were investigated by Ratcliffe & White (1930), and used to measure soil moisture by Balls (1932) who coined the term capacitance hygroscopy, and by Fletcher (1940) who measured the change in capacitance of a condenser unit having a porous-plate dielectric, buried in the soil. The method is in common use in moisture meters for grain, timber, etc. (Pande & Pande, 1962b), and development as an *in situ* method for soils seems promising now that transformer-ratio arm bridges are available for three terminal measurements. Multiple sensing heads will be needed with the capacitance method, as with the resistance block, and will be more expensive, since screened cables of stable shunt capacitance are needed. Temperature and hysteresis effects, and the power loss in a wet medium add complications.

A micro-wave meter, comprising an oscillator, receiver, and a calibrated attenuator, is commercially available for determining the moisture content of samples (Anon, 1964; Pande & Pande, 1962b). The sample is placed between receiving and transmitting antennae, a typical absorption for a 2-inch thickness of sand at 6% moisture would be 27 dB at 10,680 mc/sec. An 'S'-band version operating at 2,450 mc/sec is available for larger and wetter samples, the band frequencies being absorption bands for liquid water. The advantage of the method lies in the speed of reading. The heterogeneous nature of soils is the biggest limitation to *in situ* use of micro- or radio-wave methods. A new method based on the infra-red absorption of water compares the reflectance at wavelengths of 1.7 and 1.93*u* metre (Hoffman, 1963). The shallow penetration in soil limits the method, but longer wave lengths might improve this, making it a useful technique for measuring in the surface layer of soil, e.g., in germination studies.

Recording and processing moisture data. While it may be necessary, for some time to come, to read moisture meters visually and record manually, the ideal way to store and process readings from such an instrument is on punched cards or paper tape. This eliminates copying results onto cards or tape which is laborious and error-producing. A compromise is a manually-powered punch set up either by the operator or from the counter chain of, for example, a neutron meter. Manual-entry facilities would always be required for adding site references. Field data may be manually recorded simply and cheaply on the I.B.M. 'mark-sensed' card, but care is needed to mark clearly and to keep the cards clean. Some computer programmes to process soil-moisture data are available in computer-programme libraries, although few have been published (Marlatt & Binkowski, 1961; Pengra, 1961).

Conclusions

All present methods of soil-moisture measurement have disadvantages. Auger-sampling and thermo-gravimetric determination of moisture will be the natural choice where capital cost matters most and the effects of holes can be disregarded. The man-hours used in a big project will be considerable, and the total cost may exceed that of the neutron method. The neutron method is recommended for agronomic experiments and where repeated *in situ* measurements are needed from a site at some depth. If measurements in the top 20-cm layer are essential then smooth locations are needed for the probe. Equipment is expensive, but should have a useful life of at least 10 years. The measurement of soil suction in the wet range will often usefully supplement, but not replace, that of moisture content. For *in situ* measurements the tensiometer, with adequate replication to overcome its lack of precision, is the only choice. Pressure and vapour-pressure provide tedious but fairly accurate methods for determination of suction over a wider range in the laboratory; the latter show increasing promise.

Resistance blocks provide rather imprecise measurements over a wide range if the site is not too wet or saline. Blocks are cheap, but not long-lived, and must be well replicated. However, apart from the neutron surface probe this method is the only one for *in situ* measurements over the dry range in the top 20 cm of soil. The capacitance sensor requires further development and may prove to be a superior alternative to the resistance block.

Some of the methods listed, e.g., the infra-red, micro-wave, nuclear-magnetic-resonance and gamma methods are unproven, especially for *in situ* use, others, e.g., penetration and chemical methods are useful for special cases. Work is not complete when measurements are made, for soil variability calls for replication of readings and there may be a lot of figures to be processed. Automatic recording must arrive in soil-moisture as in other measurements, and computer programmes to process the data are becoming available.

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REFERENCES

Aitchison, G. D. and Butler, P. F. (1951). Gypsum block moisture meters as instruments for the measurement of tension in soil water. *Aust. J. appl. Sci.* **2**, 257-66.

Allyn, R. B. (1942). Calibrated soil probe for measuring field soil moisture. *Soil Sci.* **53**, 273-85.

Andreyev, S. V. and Martens, B. K. (1960). Soil moisture determination by the method of nuclear magnetic resonance. *Soviet Soil Sci.* No. 10, 1129-32.

Anon. (1961). Load cells. *Baldwin-Lima-Hamilton, Bull.* 4355A.

Anon. (1964). Microwave moisture meter. *Aust. J. Inst. Tech.* **20**, 61.

Balls, W. L. (1932). Capacitance hygroscopy and some of its applications. *Nature London* **130**, 935-8.

Barrs, H. D. (1964). *Annu. Rep. Irrigation Research Lab., Griffith, Australia 1963/4.* (Section 3,2)

Begemann, E. (1936). Determination of the water content of soil samples by means of xylene. *Proc. int. Conf. Soil Mech. and Foundation Engng* **2**, 66-7.

Bourget, S. J., Elrick, D. E. and Tanner, C. B. (1958). Electrical resistance units for moisture measurements: their moisture hysteresis, uniformity, and sensitivity. *Soil Sci.* **86**, 298-304.

Bouyoucos, G. J. (1928). Determining soil moisture rapidly and accurately by methyl alcohol. *J. amer. Soc. Agron.* **20**, 82-3.

—— (1937). Evaporating the water with burning alcohol as a means of determining moisture content of soils. *Soil Sci.* **44**, 377-81.

—— (1949). Nylon electrical resistance unit for continuous measurement of soil moisture in the field. *Soil Sci.* **67**, 319-30.

—— (1962). A continuous electric soil moisture recorder. *Agron. J.* **54**, 549.

—— and Mick, A. H. (1939). A method for obtaining a continuous measurement of soil moisture under field conditions. *J. amer. Soc. Agron.* **31**, 271.

Chahal, R. S. and Yong, R. N. (1964). Validity of the energy characteristics of soil water determined with pressurized apparatus. *Nature London* **201**, 1180-1.

Childs, E. C. (1943). Note on electrical methods of determining soil moisture. *Soil Sci.* **55**, 219-23.

Collis-George, N. (1952). Note on the pressure plate membrane apparatus. *Soil Sci.* **74**, 315-22.

Colman, E. A. and Hendrix, T. M. (1949). The fiberglas electrical soil moisture instrument. *Soil Sci.* **67**, 425-38.

Cope, F. (1962). Tensiometer design. *Annu. Rep. Irrigation Res. Lab. Griffith, Australia, 1961/62*, 9.

Croney, D., Coleman, J. D. and Currer, E. W. H. (1951). The electrical resistance method of measuring soil moisture. *Brit. J. appl. Phys.* **2**, 85-91.

Danilin, A. I. (1955). [The measurement of soil moisture by means of gamma rays.] *Pochvovedenie* **7**, 74-83.

Danne, H. A. (1912). The carbide method of determining moisture. *Chem. Engng* **16**, 163-4.

Davis, W. E. and Slater, C. S. (1942). A direct weighing method for sequent measurements of soil moisture under field conditions. *J. amer. Soc. Agron.* **34**, 285-7.

De Vries, D. A. (1953). Some results of field determination of the moisture content of soil from thermal conductivity measurements. *Neth. J. agr. Sci.* **1**, 115-21.

Edlefsen, N. E. and Anderson, A. B. C. (1941). Four electrode resistance methods for measuring soil moisture content under field conditions. *Soil Sci.* **51**, 367-76.

Ferguson, H. and Gardner, W. H. (1962). Water content measurement in soil columns by gamma ray absorption. *Soil Sci. Soc. Amer. Proc.* **26**, 11-18.

Fitzgerald, P. D. and Richard, D. S. (1963). Sampling errors associated with gravimetric soil moisture determinations. *N.Z. J. agric. Res.* **6**, 307-9.

Fletcher, J. E. (1940). Dielectric method for determining soil moisture. *Soil Sci. Soc. Amer. Proc.* **4**, 84-8.

Fraade, D. J. (1963). Measuring moisture in solids. *Instruments and Control Systems* **36**, 99-101.

Glover, J. and Forsgate, J. A. (1962). Measurement of evapotranspiration from large tanks of soil. *Nature London* **195**, 1330.

Gurr, C. G. (1962). Use of gamma rays in measuring water content and permeability in unsaturated columns of soil. *Soil Sci.* **94**, 224-9.

Haise, H. R. and Kelley, O. J. (1946). Relation of moisture tension to heat transfer and electrical resistance in plaster of paris blocks. *Soil Sci.* **61**, 411-22.

Hancock, C. K. and Burdick, R. L. (1957). Rapid determination of water in wet soils. *Soil Sci.* **83**, 197-205.

Hanks, R. J., Miller, E. E. and Tanner, C. B. (1953). Float valve pressure control for porous plate apparatus. *Soil Sci. Soc. Amer. Proc.* **17**, 318-20.

Harrold, L. L. and Dreibelbis, F. R. (1945). An accounting of the daily accretion, depletion, and storage of soil water as determined by weighing monolith lysimeters. *Trans. amer. geophys. Un.* **26**, 283-92.

Heissner, A. (1961). [A comparison of different methods of measuring soil moisture in relation to the effect of rain.] *Arch. Gartenbau* **9**, 26-49.

Hoffman, K. (1963). [Moisture measurement by infra-red reflection.] *Chem. Ing. Tech.* **35**, 55-62.

Holmes, J. W. (1956). Measuring soil water content and evaporation by the neutron scattering method. *Neth. J. agric. Sci.* **4**, 30-34.

Johnson, A. I. (1962). Methods of measuring soil moisture in the field. *U.S. geol. Survey Water-Supply Paper* 1619-*U*. U.S. Govt. Printing Office, Washington.

Kelley, O. J., Hunter, A. S., Haise, H. R. and Hobbs, C. H. (1946). Comparison of methods of measuring soil moisture under field conditions. *J. amer. Soc. Agron.* **38**, 759-84.

King, K. M., Tanner, C. B. and Suomi, V. E. (1956). A floating lysimeter and its evaporation recorder. *Trans. amer. geophys. Un.* **37**, 738-42.

Klute, A. and Peters, D. B. (1962). A recording tensiometer with a short response time. *Soil Sci. Soc. Amer. Proc.* **26**, 87-8.

Koliasev, F. E. and Kozlov, V. E. (1954). [New device for determining the compactness and moisture of the soil under field conditions.] *Vses. Akad. s.-kh. Nauk im V.I. Lenina* **19**, 33-8.

Korven, H. C. and Taylor, S. A. (1959). The Peltier effect and its use for determining the relative activity of soil water. *Canad. J. Soil Sci.* **39**, 76-85.

Kubo, J. (1953). A new method for the soil moisture measurement. *J. agric. Meteorol. Tokyo* **8**, 108-10.

Lawless, G. P., MacGillivray, N. A. and Nixon, P. R. (1963). Soil moisture interface effects upon readings of neutron moisture probes. *Soil Sci. Soc. Amer. Proc.* **27**, 502-7.

Leonard, R. A. and Low, P. F. (1962). A self adjusting null-point tensiometer. *Soil Sci. Soc. Amer. Proc.* **26**, 123-5.

Lull, H. W. and Reinhart, K. G. (1955). Soil moisture measurement. *U.S.D.A. Southern Forest Exp. Sta. Occasional Paper* **140**, 56.

Marlatt, W. E. and Binkowski, F. S. (1961). A rapid method for calculating soil moisture content from gravimetric samples. *Agron. J.* **53**, 134.

Marshall, T. J. (1959). Relations between water and soil. *Commonw. Bur. Soils tech. Commun.* **50**.

Miller, R. D. (1951). Technique of measuring soil moisture tensions in rapidly changing systems. *Soil Sci.* **72**, 291-301.

Momin, A. U. (1945). A new simple method of estimating the moisture content of soil *in situ*. *Indian J. agric. Sci.* **17**, 81-5.

Monteith, J. L. and Owen, P. C. (1958). A thermocouple method for measuring relative humidity in the range 95-100%. *J. sci. Instrum.* **35**, 443-6.

Mukhin, L. M. and Chistotinov, L. V. (1961). Gamma ray method of determining moisture in coarse fragmentary soils. *Soviet Soil Sci.* No. 7, 807-9.

Orchiston, H. D. (1953). Adsorption of water vapour. I. Soils at 25°C. *Soil Sci.* **76**, 453-65.

Pande, A. and Pande, C. S. (1962). Physical methods of moisture measurement.

—— —— (1962a). Part 1. *Instrument Practice* **16**, 896-903.

—— —— (1962b). Part 2. *Instrument Practice* **16**, 988-95.

—— —— (1962c). Part 3. *Instrument Practice* **16**, 1104-10.

—— —— (1962d). Part 4. *Instrument Practice* **16**, 1246-50.

Papadakis, J. S. (1941). Rapid method of determining soil moisture. *Soil Sci* .**51**, 279-81.

Peck, A. J. (1960). Change of moisture tension with temperature and air pressure: theoretical. *Soil Sci.* **89**, 303-10.

Pengra, R. F. (1961). Instruction for use of the 602A I.B.M. Calculator for daily soil moisture accounting. *Climatology* **14**, 265-81. (Laboratory of Climatology, Centerton, N.J.).

Popov, L. V. (1960). [Methods for determination of moisture content of soil.] *Trudȳ vost.-sibirsk. Fil. sibirsk. Otd. Akad. Nauk* **1**, 96.

Postlethwaite, J. D. and Trickett, E. S. (1956). The measurement of soil moisture. *J. agric. Engng Research* **1**, 89-95.

Quirk, J. P. (1954). Vapour losses from the pressure membrane apparatus. *Soil Sci.* **78**, 411-2.

Ratcliffe, J. A. and White, F. F. W. (1930). Electrical properties of soil at radio frequencies. *Phil. Mag.* **10**, 667.

Reitemeyer, R. F. and Richards, L. A. (1944). Reliability of the pressure membrane method for extraction of soil solution. *Soil Sci.* **57**, 119-35.

Richards, L. A. (1941). A pressure membrane extraction apparatus for soil solution. *Soil Sci.* **51**, 377-86.

—— (1947). Pressure membrane apparatus, contruction and use. *Agric. Engng* **28**, 451-4.

—— (1949). Methods of measuring soil moisture tension. *Soil Sci.* **68**, 95-112.

—— and Ogata, G. (1958). Thermocouple for vapour pressure measurements in biological and soil systems at high humidity. *Science* **128**, 1089-90.

Richards, S. J. (1938). Soil moisture content calculations from capillary tension records. *Soil Sci. Soc. Amer. Proc.* **3**, 57-64.

Robinson, R. A. and Stokes, R. H. (1959). Electrolyte solutions, 2nd Ed. Butterworths Scientific Publications, London.

Sabitov, M. A. (1961). Influence of the time of sample weighing on the accuracy of soil moisture determinations. *Soviet Soil Sci.* No. 6, 676-8.

Shaw, B. T. and Baver, L. D. (1939). An electrothermal method for following moisture changes in soil *in situ*. *Soil Sci. Soc. Amer. Proc.* **4**, 78-83.

Shaw, M. D. and Arble, W. C. (1959). Bibliography on methods for determining soil moisture. *Penn. State Univ. Coll. Agric., Engng Res. Bull.* **B-78**.

Spanner, D. C. (1951). The Peltier effect and its use in the measurement of suction pressure. *J. exp. Bot.* **2**, 145-68.

Stace, H. C. T. and Palm, A. W. (1962). A thin walled tube for core sampling of soils. *Aust. J. exp. Agric. Anim. Husb.* **2**, 238-41.

Sweeny, R. (1962). Measurements of soil moisture and density by nuclear methods. A.E.R.E. Bibl. No. 140, H.M.S.O., London.

Talsma, T. T. (1964). *Annu. Rep. Irrig. Res. Lab. Griffith, Australia, 1963-4.*

Taylor, G. S. (1952). A portable four-electrode probe for measuring soil moisture. *Iowa. State Coll. J. Sci.* **26**, 299-301.

Taylor, S. A., Evans, D. D. and Kemper, W. D. (1961). Evaluating soil water. *Utah agric. exp. Sta. Bull.* **426**.

Teterin, P. P. (1956). [Universal moisture meter.] *Gidrotekh. i Melior.* **8**, 56-7.

Thijsen, H. A. C., Wit, C. T. de, Vollenhoven, E. van, et al. (1954). New instruments for agricultural research. *Neth. J. agric. Sci.* **2**, 209-14.

Van Bavel, C. H. M. (1958). Measurement of soil moisture content by the neutron method. *USDA. ARS.* **41-24**, pp 29.

—— (1962). Accuracy and source strength in soil moisture neutron probes. *Proc. Soil Sci. Soc. Amer.* **26**, 405.

—— and Myers, L. E. (1962). An automatic weighing lysimeter. *Agric. Engng* **43**, 580-3, 586-8.

Van Duin, R. H. A. and De Vries, D. A. (1954). A recording apparatus for measuring thermal conductivity, and some results obtained with it in soil. *Neth. J. agr. Sci.* **2**, 166-175.

Veihmeyer, F. J. (1929). An improved soil sampling tube. *Soil Sci.* **27**, 147-52.

Wells, C. B. (1959). Core samplers for soil profiles. *J. agric. Engng Res.* **4**, 260-6.

Wijk, W. R. van. (1963). Physics of Plant Environment. N. Holland Publishing Co., 162-6.

Wilde, S. A. and Spyridakis, D. M. (1962). Determination of soil moisture by the immersion method. *Soil Sci.* **94**, 132-3.

Winter, E. J. (1963). A new type of lysimeter. *J. hort. Sci.* **38**, 160-8.